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1. INTRODUCTION[1]

Shipboard Scientific Party[2]

The Blake-Bahama Outer Ridge (BBOR) and Carolina Slope (CS) form the western boundary for deep- and surface-water circulation in the subtropical North Atlantic. Between the northward-flowing surface waters of the Gulf Stream and the net southerly flow of intermediate and deep waters, most of the climatically important exchanges of heat, salt, and water with other ocean basins occur in the westernmost North Atlantic. At the deepest levels of the western North Atlantic, Antarctic Bottom Water (AABW) flows northward and blends with several other water masses in the deep recirculating gyres to form the North Atlantic Deep Water (NADW) (Fig. 1). The western intensification and flow of these waters erode the continental margin in some locations and preferentially deposit sediments at other locations known as sediment drifts.

The main focus of Ocean Drilling Program (ODP) Leg 172 was to recover a sequence of high deposition-rate sediment cores from sediment drifts in the western North Atlantic that document rapid changes in climate and ocean circulation during the middle Pliocene to Pleistocene times (Figs. 2, 3). Leg 172 sediments are also useful for their high-resolution history of magnetic field behavior and their history of biotic change. In addition, the sedimentary microstructure at Leg 172 sites reflects the combination of both downslope and along-slope depositional processes. Finally, high deposition rates and high organic carbon content along the eastern U.S. continental margin set the stage for biogenic methane production and clathrate formation. This is of direct interest to paleoceanographers and sedimentologists because gas disrupts the fabric of piston core sediments and interferes with operation of the advanced piston corer (APC), but it is of more widespread interest because methane is a powerful "greenhouse" gas.

Leg 172 builds on previous scientific ocean drilling in the western North Atlantic. During Deep Sea Drilling Project (DSDP) Leg 2 the northeastern Bermuda Rise was drilled to date the sediments overlying basement as a first test of seafloor spreading and to date a prominent change in the acoustic character of the sediments (Hays, et al., 1972). The objectives, however, were not achieved because the sediments were unfossiliferous and because of technical difficulties. Results of DSDP Leg 11 drilling suggested that a strong reflector on the Blake Outer Ridge was a result of gas hydrate (Hollister, Ewing, et al., 1972), but that conjecture was not confirmed until DSDP Leg 76 revisited the Blake Outer Ridge (Sheridan, Gradstein, et al., 1983). Most recently, this region was the focus of ODP Leg 164, which was dedicated to studying the formation of gas hydrate and estimating its abundance (Paull, Matsumoto, Wallace, et al., 1996).

SEDIMENT DRIFTS

Sediment drifts are widespread in the North Atlantic basin and reflect both the abundant sources of sediment and its focusing by deep currents (Lonsdale, 1982; McCave and Tucholke, 1986). There is at least one sediment drift associated with every water mass in the North Atlantic, suggesting the potential for tracing the individual components of NADW on geological time scales using geochemical and sedimentological techniques (Keigwin and Jones, 1989). Although drift sedimentation has been the subject of comprehensive studies in the North Atlantic (e.g., Heezen et al., 1966; Silva et al., 1976; Flood, 1978; Laine and Hollister, 1981; McCave et al., 1982), sediment drifts have been exploited only recently for their high-resolution paleoceanographic and paleoclimatic information (e.g., Ledbetter and Balsam, 1985; Boyle and Keigwin, 1987; Broecker et al., 1988; Johnson et al., 1988; Haskell et al., 1991; Keigwin and Jones, 1994; McCave et al., 1995). Within the scientific ocean drilling community, sediment drifts have been the subject of concentrated paleoclimate study only during DSDP Leg 94, which cored sites on Feni Drift and on Gardar Drift (Ruddiman, Kidd, Thomas, et al., 1987), and during ODP Leg 162, during which additional sites on Feni and Gardar Drifts, as well as on Bjorn Drift (Jansen, Raymo, Blum, et al., 1996) were cored.

One of the most intensively studied sediment drifts in the North Atlantic lies on the northeast Bermuda Rise (BR), where the overlying deep water is the most turbid in the basin (Biscaye and Eittreim, 1977) as a result of the advection of clays and silts by the deep Gulf Stream return flow (Laine and Hollister, 1981; see also Hogg, 1983, and Schmitz and McCartney, 1993). The ultimate source of this terrige-

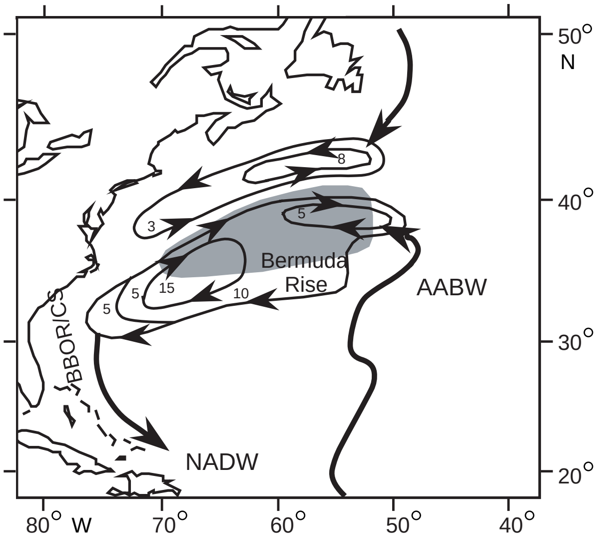

Figure 1. Schematic of circulation patterns in the deep western North Atlantic (updated from Schmitz and McCartney, 1993; by M.S. McCartney, in a pers. comm. to L. Keigwin, 1995). The thin lines represent streamlines of two recirculating gyres and the small numbers are approximate transport in Sverdrups (1 Sv = 10^6 m^3s^{-1}). Thick lines represent generalized flow direction of AABW and NADW, which contribute to the Deep Western Boundary Current. The shaded pattern marks the region of high surface eddy kinetic energy (EKE), deep EKE, and deep suspended sediment. Note that, in this scheme, the southern recirculating gyre over the Bermuda Rise is the mixing zone for northern- and southern-origin waters, and that true "NADW" is formed in that mixing zone.

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[2] Shipboard Scientific Party is given in the list preceding the Table of Contents.

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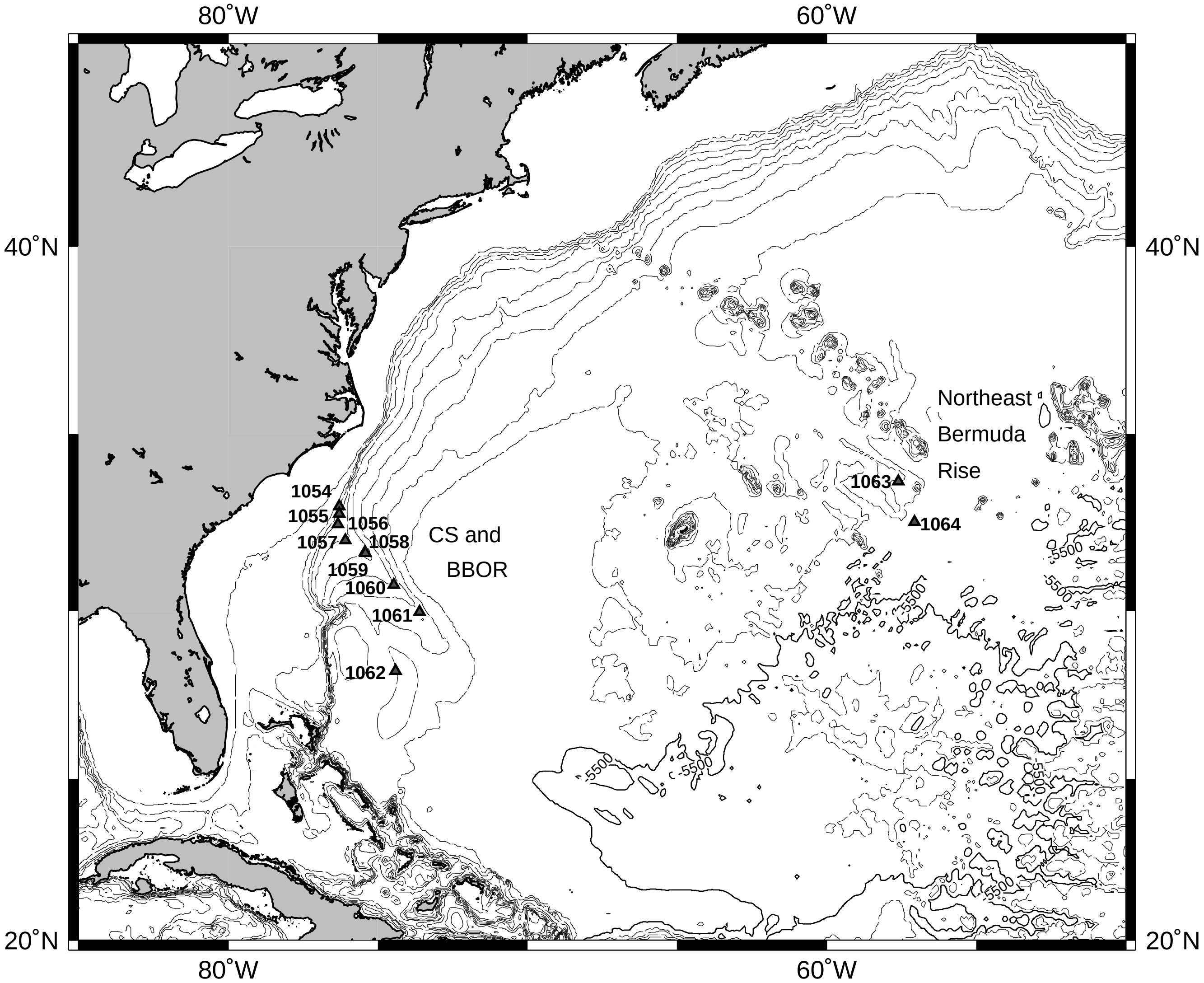

Figure 2. Map of the western North Atlantic Ocean showing the location of Leg 172 sites on the northeast Bermuda Rise (Site 1063), the Sohm Abyssal Plain (Site 1064), the Carolina Slope (CS; Sites 1054 and 1055), and the Blake-Bahama Outer Ridge (BBOR; Sites 1056–1062).

nous sediment is probably eastern Canada, although Laine et al. (1994) document local erosion on the eastern scarp of the BR and redeposition on its plateau. During glaciation, deposition rates were as high as 200 cm/k.y. on the BR (Keigwin and Jones, 1989). Geochemical studies of cores from the BR have revealed the coupling of the ocean, the atmosphere, and ice sheets on the submillennial scale. For example, deep-ocean circulation at that location (~4500 m) responded to the Younger Dryas cooling episode (Boyle and Keigwin, 1987), as well as to earlier oscillations in the climate system (Keigwin et al., 1991; Keigwin and Jones, 1994).

A PALEOCEANOGRAPHIC DEPTH TRANSECT

It is difficult to understand the ocean-climate system from the study of single core locations. For example, paleochemical results from BR cores illustrate changes in deep-ocean circulation from only one water depth (4500 m) because the northeast BR is a plateau. Proxy data for deep-ocean nutrient content at that location show large changes with time, but we cannot distinguish between latitudinal changes in the mixing zone between southern- and northern-source waters and changes caused by vertical migration of a benthic front. Groups of sites must be located across a range of depths to study the ocean in three dimensions.

Paleo-environmental depth transects were identified as a first priority of the Committee on Scientific Ocean Drilling II (COSOD II, 1987). Such transects have been cored in the eastern equatorial Atlantic (Leg 108), the subantarctic (Leg 113), the Indian Ocean (Leg 115), the Arabian Sea (Leg 117), the western equatorial Pacific (Leg 130), and the western equatorial Atlantic (Leg 154).

Most of the depth transect is on the Blake Outer Ridge, which is ideal for this purpose. As noted by Markl and Bryan (1983), “The Blake Outer Ridge is the largest sediment ridge known. Its existence, orientation, and internal structure reflect major events in the evolution of the western North Atlantic Ocean.” Large vertical gradients can be expected in the Tertiary and Quaternary oceans. In addition to monitoring water-mass variability in the late Neogene, Leg 172 sites will be used to monitor important basinwide changes in the position of the lysocline, which may be additionally influenced at this location by the position of the Deep Western Boundary Current (DWBC) (Balsam, 1982). Grain size results on the Blake Outer Ridge are consistent with nutrient proxy results as monitors of deglaciation changes in deep-ocean circulation, indicating there were important glacial–interglacial changes in the intensity and position of

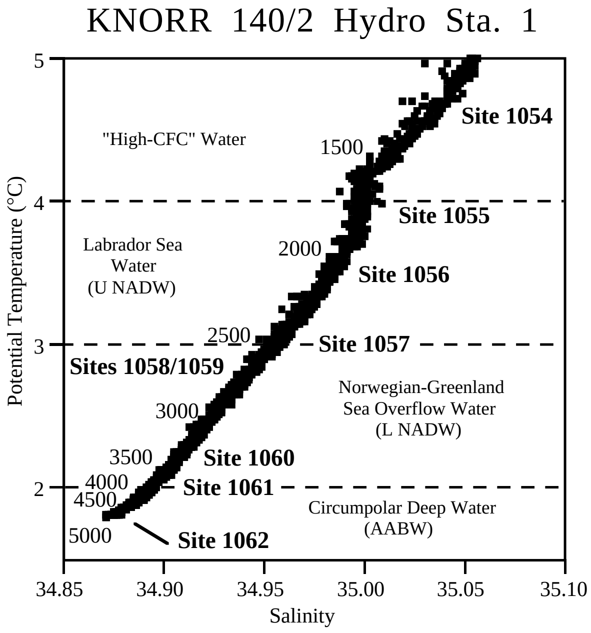

Figure 3. Position of Leg 172 BBOR sites with respect to water masses in the western subtropical North Atlantic. Water depths are indicated every 500 m along the temperature/salinity plot. Sites were chosen so that at least one lies within each modern water mass and one lies at the boundary between water masses. This depth distribution of sites is required to monitor the most likely changes in water masses and their boundaries through the late Neogene. U = upper; L = lower. *KNORR* 140/2 Hydro Sta. 1 refers to the site survey cruise and station number that were used to collect the data.

the DWBC on the Blake Outer Ridge (Haskell, 1991; Haskell et al., 1991). A depth transect of these data for time slices will for the first time document the bathymetric extent of these circulation changes.

Eleven sites were cored during Leg 172: seven on the BBOR, two on the Carolina Slope, one on the Bermuda Rise, and one on the Sohm Abyssal Plain (Fig. 2; Table 1). The main purpose of Leg 172 was to provide a latest Neogene depth transect for documenting changes in the depth distribution of water masses (Fig. 3). The geographic range of sites may also help distinguish between latitudinal changes in the mixing zone between southern and northern source waters and changes caused by vertical migration of a benthic front, especially when considered in the context of other recent ODP legs such as Legs 154 and 162. The Leg 172 depth transect off the U.S. east coast is especially important because this margin forms a western boundary for deep currents (Stommel, 1958) that follow depth contours (Heezen et al., 1966). Above ~4000 m depth, these waters mostly have a northern source, whereas at greater depths there is a greater proportion of recirculated southern-source water (Hogg, 1983). Sites 1054 and 1055 monitor the shallowest components of NADW, which originate in and near the Labrador Sea and can be traced using chlorofluorocarbons (CFCs) (Pickart and Smethie, 1993). This water mass is expected to wax and wane on glacial–interglacial and millennial time scales, out of phase with the production of Lower NADW (Boyle and Keigwin, 1987; Oppo and Lehman, 1993). Reconstructions of glacial North Atlantic hydrography show that the hinge point between better ventilated waters at intermediate depth and more poorly ventilated deep waters occurs at ~2000 m. This boundary is bracketed by Sites 1055 and 1056, which are positioned to detect changes in its depth. Likewise, Site 1058 is located at the interface between Upper NADW and Lower NADW. Sites 1059 and 1060, which lie within the core of Lower NADW, should be insensitive to all but the largest changes in benthic fronts between the AABW, Lower NADW, and Upper NADW. Finally, our deepest sites (Sites 1061–1064) are situated to record distinctive changes in the AABW/Lower NADW front (Keigwin et al., 1994).

MUD-WAVE DYNAMICS

Recent studies of mud-wave dynamics suggest that mud waves migrate because there are cross-wave changes in bed shear stress (Flood, 1988; Blumsack and Weatherly, 1989). In the case of fine-grained cohesive sediment, the accumulation rate decreases as shear stress increases (McCave and Swift, 1976); thus, less sediment accumulates on the wave flank with the higher flow speed. In the case of a lee-wave flow pattern, flows on the upcurrent, upslope wave flank are weaker than those on the downcurrent wave flank, leading to upslope and upcurrent wave migration. Enhanced wave migration is expected at higher flow speeds because currents on the downcurrent flank approach the critical shear stress for deposition before those on the upcurrent flank (Flood, 1988).

Wave migration can be measured by determining the ratio of sediment thickness deposited on each wave flank during a time interval or between two correlated layers, and a model-dependent flow speed can be estimated (Flood, 1988). This approach was used with success in the Argentine Basin, where a mud wave appears to have become inactive during the last 20–30 k.y. (Manley and Flood, 1992). Unfortunately, the Argentine Basin lies under very corrosive deep water, which prevents the preservation of calcareous benthic foraminifers and the recovery of chemical proxy data for ocean paleocirculation. Independent evidence of changes in flow speed should be made in concert with interpretations of circulation change made on the basis of ocean paleochemistry.

Wave migration on sediment drifts has been a long-standing ODP interest, but it had not yet been successfully addressed until Leg 172. As the Sedimentary and Geochemical Processes Panel (SGPP) White Paper (*JOIDES* Journal, 1990) states,

> The history of thermohaline bottom current processes is preserved in sediment drifts and sediment waves molded under relatively steady currents. Drilling transects will test sedimentation models for sediment structure and bottom current depositional processes and use these models to determine past variations in the bottom flow regime of the ocean.

Waveforms observed at DSDP Sites 610 and 611 were found to be surprisingly stable, migrating on a million-year time scale (Kidd and Hill, 1987). However, that study sampled wave crests and troughs, not wave flanks. Evidence from the Bahama Outer Ridge (Flood, 1978) and the Argentine Basin (Manley and Flood, 1992), as well as wave models, suggests that the largest difference in sedimentation rates is to be expected on the flanks. The Bahama Outer Ridge wave field is mapped with much greater precision than those on Gardar and Feni Drifts, and carbonate content in small free-fall cores indicates that sedimentation rates did indeed change between upstream and downstream wave flanks during the latest Quaternary (Flood, 1978).

GAS HYDRATE AND PORE-WATER GEOCHEMISTRY

The world's best-known marine gas hydrate occurrence is located within the operating area of Leg 172 on the Blake Outer Ridge and Carolina Slope. Three DSDP-ODP legs in the Blake Ridge area (Fig. 4) have recovered gas hydrate and/or found pore-water signatures indicating its presence: DSDP Leg 11 (Sites 102, 103, and 104; Hollister, Ewing, et al., 1972); DSDP Leg 76 (Site 533; Sheridan, Gradstein, et al., 1983); and ODP Leg 164 (Paull, Matsumoto, Wallace, et al., 1996). Gas hydrate, present on continental margins worldwide

Table 1. Leg 172 drilling results.

Hole	Latitude	Longitude	Water depth (mbrf)	Number of cores	Interval cored (m)	Core recovered (m)	Recovery (%)	Total penetration (m)
1054A	33°0.0001′N	76°16.9996′W	1302.5	22	200.00	182.55	91.3	200.00
1054B	32°59.9850′N	76°16.9999′W	1304.8	12	103.20	106.29	103.0	103.20
1054C	32°59.9676′N	76°16.9995′W	1305.9	13	101.90	104.55	102.6	101.90
			Site 1054 totals:	47	405.10	393.39	97.1	405.10
1055A	32°47.0418′N	76°17.1703′W	1810.0	1	9.50	9.82	103.4	9.50
1055B	32°47.0406′N	76°17.1790′W	1809.0	14	128.00	137.99	107.8	128.00
1055C	32°47.0562′N	76°17.1798′W	1809.0	14	120.80	126.10	104.4	120.80
1055D	32°47.0711′N	76°17.1792′W	1809.9	14	129.10	136.99	106.1	129.10
1055E	32°47.0925′N	76°17.1799′W	1809.0	2	18.00	18.48	102.7	18.00
			Site 1055 totals:	45	405.40	429.38	105.9	405.40
1056A	32°29.0995′N	76°19.8025′W	2178.0	1	9.50	9.98	105.1	9.50
1056B	32°29.1018′N	76°19.7988′W	2177.9	17	155.60	171.81	110.4	155.60
1056C	32°29.1105′N	76°19.8113′W	2178.2	17	154.80	166.25	107.4	154.80
1056D	32°29.1215′N	76°19.8253′W	2177.7	13	121.80	132.46	108.8	121.80
			Site 1056 totals:	48	441.70	480.50	108.8	441.70
1057A	32°1.7507′N	76°4.7527′W	2595.0	14	131.00	141.67	108.1	131.00
1057B	32°1.7317′N	76°4.7538′W	2595.8	15	136.70	145.08	106.1	136.70
1057C	32°1.7141′N	76°4.7546′W	2594.5	8	73.50	77.46	105.4	73.50
			Site 1057 totals:	37	341.20	364.21	106.7	341.20
1058A	31°41.4153′N	75°25.8049′W	2996.0	16	152.00	164.56	108.3	152.00
1058B	31°41.4022′N	75°25.8038′W	2995.5	17	158.00	166.00	105.1	158.00
1058C	31°41.3861′N	75°25.8014′W	2996.0	18	164.00	173.81	106.0	164.00
			Site 1058 totals:	51	474.00	504.37	106.4	474.00
1059A	31°40.4610′N	75°25.1270′W	2996.7	11	98.80	105.49	106.8	98.80
1059B	31°40.4528′N	75°25.1121′W	2996.8	10	92.20	95.91	104.0	92.20
1059C	31°40.4421′N	75°25.0983′W	2996.0	10	95.00	100.54	105.8	95.00
			Site 1059 totals:	31	286.00	301.94	105.6	286.00
1060A	30°45.5971′N	74°27.9897′W	3492.5	18	170.10	177.74	104.5	170.10
1060B	30°45.5849′N	74°27.9887′W	3492.1	14	129.90	134.23	103.3	129.90
1060C	30°45.5682′N	74°27.9896′W	3492.5	14	126.50	130.78	103.4	126.50
			Site 1060 totals:	46	426.50	442.75	103.8	426.50
1061A	29°58.4976′N	73°35.9929′W	4058.0	37	350.30	298.20	85.1	350.30
1061B	29°58.5172′N	73°35.9914′W	4055.0	1	9.50	9.82	103.4	9.50
1061C	29°58.5154′N	73°35.9923′W	4048.2	18	166.80	174.61	104.7	166.80
1061D	29°58.5326′N	73°35.9900′W	4049.8	22	180.00	194.95	108.3	180.00
1061E	29°58.5563′N	73°35.9933′W	4047.1	2	18.90	19.53	103.3	18.90
			Site 1061 totals:	80	725.50	697.11	96.1	725.50
1062A	28°14.7819′N	74°24.4192′W	4774.8	20	180.70	181.24	100.3	180.70
1062B	28°14.7888′N	74°24.4204′W	4774.5	26	239.00	239.08	100.0	248.60
1062C	28°14.7954′N	74°24.4163′W	4772.1	14	132.90	134.56	101.2	132.90
1062D	28°14.7998′N	74°24.4157′W	4771.7	9	81.80	82.66	101.1	81.80
1062E	28°14.7653′N	74°25.0552′W	4785.7	23	208.80	203.72	97.6	208.80
1062F	28°14.7710′N	74°25.0651′W	4785.4	9	83.10	83.77	100.8	83.10
1062G	28°14.7548′N	74°24.6218′W	4759.2	1	9.30	9.27	99.7	9.30
1062H	28°14.7537′N	74°24.6204′W	4757.0	7	63.50	65.29	102.8	63.50
			Site 1062 totals:	109	999.10	999.59	100.0	1008.70
1063A	33°41.2043′N	57°36.8979′W	4595.2	45	418.40	400.34	95.7	418.40
1063B	33°41.1885′N	57°36.8982′W	4594.7	38	351.60	341.95	97.3	351.60
1063C	33°41.1808′N	57°36.9028′W	4596.0	24	212.70	204.39	96.1	212.70
1063D	33°41.1717′N	57°36.9067′W	4596.2	19	173.10	176.54	102.0	173.10
			Site 1063 totals:	126	1155.80	1123.22	97.2	1155.80
1064A	32°32.7199′N	57°4.5876′W	5580.0	3	28.50	28.83	101.2	28.50
			Site 1064 totals:	3	28.50	28.83	101.2	28.50
			Leg 172 totals:	623	5688.80	5765.29	101.3	5698.40

(e.g., Shipley et al., 1979; Kvenvolden, 1988), is important because it may (1) affect the Earth's climate through storage and release of methane, a greenhouse gas (e.g., Nisbet, 1989; Paull et al., 1991); (2) cause sediment slumping on continental margins (e.g., Carpenter, 1981; Popenoe et al., 1993; Paull et al., 1996); and (3) influence the diagenesis of continental rise sediments (e.g., Lancelot and Ewing, 1972; Matsumoto, 1983; Borowski et al., 1996, 1997).

The presence of gas hydrate in the BBOR/CS region was of particular concern during Leg 172 for two reasons. First, it was found during both DSDP Leg 76 and ODP Leg 164 that gas charging and sediment diagenesis associated with gas hydrate prevented successful operation of the APC at sub-bottom depths greater than 150 m. Second, although the acoustic signature of gas hydrate is not present in the BBOR region at water depths >4 km, Leg 164 scientists found that the absence of the acoustic signature (the bottom-simulating reflector [BSR]) does not mean the absence of gas hydrate.

Gas hydrate occurrence is usually inferred from the appearance of a BSR on seismic reflection profiles (Tucholke et al., 1977). However, geochemical concentration and isotopic profiles are potentially more sensitive indicators of underlying gas hydrate than established seismic detection methods (Borowski et al., 1996). For example, Site 994 (Leg 164) displays no BSR but possesses the following pore-

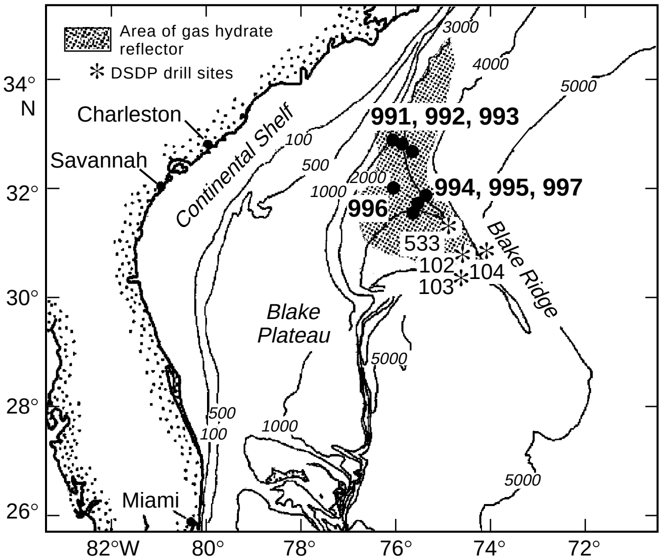

Figure 4. Map showing the outline of the Blake Outer Ridge gas hydrate field (stippled). Gas hydrate is typically detected by the presence of a bottom simulating reflector (BSR) on seismic reflection profiles. The gas hydrate outline is based on mapping the presence of BSRs (from Dillon and Paull, 1983; modified after Paull, Matsumoto, Wallace, et al., 1996).

water anomalies that strongly suggest the presence of underlying gas hydrate (Paull, Matsumoto, Wallace, et al., 1996): (1) chloride concentration decreases with depth, probably reflecting dissociation of gas hydrate at the base of the stability zone and upward migration of fresher fluids (Hesse and Harrison, 1981; Ussler and Paull, 1995); (2) the sulfate concentration profile decreases linearly, suggesting an upward methane flux from gas hydrate below (Borowski et al., 1996); and (3) extreme depletion of ^{13}C occurs within the interstitial methane and CO_2 pools at shallow depths (Borowski et al., 1997).

ODP Leg 172 drilled holes both inside and outside of the mapped distribution of BSRs of the Blake Ridge hydrate field (Fig. 4). The leg thus provides an opportunity to (1) assess the lateral distribution of gas hydrate and its related geochemical signatures within the continental rise and (2) assess the linkage of various geochemical patterns to diagenetic processes that may be directly or indirectly caused by gas hydrate. These data are critical to improve estimates of the size of the gas hydrate reservoir in the Blake Ridge area (and elsewhere) and to understand the geochemical processes involved in the development of extensive gas hydrate fields.

REFERENCES

Balsam, W.L., 1982. Carbonate dissolution and sedimentation on the Mid-Atlantic continental margin. *Science,* 217:929–931.

Biscaye, P.E., and Eittreim, S.L., 1977. Suspended particulate loads and transports in the nepheloid layer of the abyssal Atlantic Ocean. *Mar. Geol.,* 23:155–172.

Blumsack, S.L., and Weatherly, G.L., 1989. Observations of the nearby flow and a model for the growth of mud waves. *Deep-Sea Res. Part A,* 36:1327–1339.

Borowski, W.S., Paull, C.K., and Ussler, W., III, 1996. Marine pore-water sulfate profiles indicate in situ methane flux from underlying gas hydrate. *Geology,* 24:655–658.

————, 1997. Carbon cycling within the upper methanogenic zone of continental rise sediments: an example from the methane-rich sediments overlying the Blake Ridge gas hydrate deposits. *Mar. Chem.,* 57:299–311.

Boyle, E.A., and Keigwin, L.D., 1987. North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature. *Nature,* 330:35–40.

Broecker, W.S., Andree, M., Wölfli, W., Oeschger, H., Bonani, G., Kennett, J.P., and Peteet, D., 1988. The chronology of the last deglaciation: implications to the cause of the Younger Dryas event. *Paleoceanography,* 3:1–19.

Carpenter, G.B., 1981. Coincident sediment slump/clathrate complexes on the U.S. Atlantic continental slope. *Geo-Mar. Lett.,* 1:29–32.

COSOD II, 1987. *Rep. 2nd Conf. Scientific Ocean Drilling:* Washington/Strasbourg (JOIDES/European Sci. Found.).

Dillon, W.P., and Paull, C.K., 1983. Marine gas hydrates, II. Geophysical evidence. *In* Cox, J.L. (Ed.), *Natural Gas Hydrates: Properties, Occurrences, and Recovery:* Woburn, MA (Butterworth), 73–90.

Flood, R.D., 1978. Studies of deep-sea sedimentary microtopology in the North Atlantic Ocean [Ph.D. dissert.]. Woods Hole Oceanographic Inst./Massachusetts Inst. of Technology.

————, 1988. A lee wave model for deep-sea mud wave activity. *Deep-Sea Res. Part A,* 35:973–983.

Haskell, B.J., 1991. The influence of deep western North Atlantic circulation on Late Quaternary sedimentation on the Blake Outer Ridge [Ph.D. thesis]. Duke Univ.

Haskell, B.J., Johnson, T.C., Lynch, E.L., and Showers, W.J., 1991. Fluctuations in deep western North Atlantic circulation on the Blake Outer Ridge during the last deglaciation. *Paleoceanography,* 6:21–31.

Hays, J.D., et al., 1972. *Init. Repts. DSDP,* 9: Washington (U.S. Govt. Printing Office).

Heezen, B.C., Hollister, C.D., and Ruddiman, W.F., 1966. Shaping of the continental rise by deep geostrophic contour currents. *Science,* 152:502–508.

Hesse, R., and Harrison, W.E., 1981. Gas hydrates (clathrates) causing pore-water freshening and oxygen isotope fractionation in deep-water sedimentary sections of terrigenous continental margins. *Earth Planet. Sci. Lett.,* 55:453–462.

Hogg, N.G., 1983. A note on the deep circulation of the Western North Atlantic: its nature and causes. *Deep-Sea Res. Part A,* 9:945–961.

Hollister, C.D., Ewing, J.I., et al., 1972. *Init. Repts. DSDP,* 11: Washington (U.S. Govt. Printing Office).

Jansen, E., Raymo, M.E., Blum, P., et al., 1996. *Proc. ODP, Init. Repts.,* 162: College Station, TX (Ocean Drilling Program).

Johnson, T.C., Lynch, E.L., and Showers, W.J., 1988. Pleistocene fluctuations in the Western Boundary Undercurrent on the Blake Outer Ridge. *Paleoceanography,* 3:191–207.

JOIDES Journal, 1990. Sedimentary and geochemical processes panel: white paper. *JOIDES J.,* 16:45–60.

Keigwin, L.D., Curry, W.B., Lehman, S.J., and Johnsen, S., 1994. The role of the deep ocean in North Atlantic climate change between 70 and 130 kyr ago. *Nature,* 371:323–326.

Keigwin, L.D., and Jones, G.A., 1989. Glacial-Holocene stratigraphy, chronology, and paleoceanographic observations on some North Atlantic sediment drifts. *Deep-Sea Res.,* 36:845–867.

————, 1994. Western North Atlantic evidence for millennial-scale changes in ocean circulation and climate. *J. Geophys. Res.,* 99:12397–12410.

Keigwin, L.D., Jones, G.A., Lehman, S.J., and Boyle, E.A., 1991. Deglacial meltwater discharge, North Atlantic deep circulation, and abrupt climate change. *J. Geol. Res.,* 96(NC9):16811–16826.

Kidd, R.B., and Hill, P.R., 1987. Sedimentation on Feni and Gardar sediment drifts. *In* Ruddiman, W.F., Kidd, R.B., Thomas, E., et al., *Init. Repts. DSDP,* 94 (Pt. 2): Washington (U.S. Govt. Printing Office), 1217–1244.

Kvenvolden, K.A., 1988. Methane hydrate—a major reservoir of carbon in the shallow geosphere? *Chem. Geol.,* 71:41–51.

Laine, E.P., Gardner, W.D., Richardson, M.J., and Kominz, M.A., 1994. Abyssal currents and advection of resuspended sediment along the northeastern Bermuda Rise. *Mar. Geol.,* 119:159–171.

Laine, E.P., and Hollister, C.D., 1981. Geological effects of the Gulf Stream system on the northern Bermuda Rise. *Mar. Geol.,* 39:277–310.

Lancelot, Y., and Ewing, J.I., 1972. Correlation of natural gas zonation and carbonate diagenesis in Tertiary sediments from the north-west Atlantic. *In* Hollister, C.D., Ewing, J.I., et al., *Init. Repts. DSDP,* 11: Washington (U.S. Govt. Printing Office), 791–799.

Ledbetter, M.T., and Balsam, W.L., 1985. Paleoceanography of the Deep Western Boundary Undercurrent on the North American continental margin for the past 25,000 yr. *Geology,* 13:181–184.

Lonsdale, P., 1982. Sediment drifts of the Northeast Atlantic and their relationship to the observed abyssal currents. *Bull. Inst. Geol. Bassin d'Aquitain,* 31:141–149.

Manley, P.L., and Flood, R.D., 1992. Paleoflow history determined from mud wave migration: Argentine Basin. *Deep-Sea Res. Part A,* 40:1033–1055.

Markl, R.G., and Bryan, G.M., 1983. Stratigraphic evolution of the Blake Outer Ridge. *AAPG Bull.,* 67:663–683.

Matsumoto, R., 1983. Mineralogy and geochemistry of carbonate diagenesis of the Pliocene and Pleistocene hemipelagic mud on the Blake Outer Ridge, Site 533, Leg 76. *In* Sheridan, R.E., Gradstein, F.M., et al., *Init. Repts. DSDP,* 76: Washington (U.S. Govt. Printing Office), 411–427.

McCave, I.N., Hollister, C.D., Laine, E.P., Lonsdale, P.F., and Richardson, M.J., 1982. Erosion and deposition on the eastern margin of the Bermuda Rise in the late Quaternary. *Deep-Sea Res. Part A:* 29:535–561.

McCave, I.N., Manighetti, B., and Beveridge, N.A.S., 1995. Circulation in the glacial North Atlantic inferred from grain-size measurements. *Nature,* 374:149–152.

McCave, I.N., and Swift, S.A., 1976. A physical model for the rate of deposition of fine-grained sediments in the deep sea. *Geol. Soc. Am. Bull.,* 87:541–546.

McCave, I.N., and Tucholke, B.E., 1986. Deep current-controlled sedimentation in the western North Atlantic. *In* Vogt, P.R., and Tucholke, B.E. (Eds.), *The Western North Atlantic Region.* Geol. Soc. Am., Geol. of North Am. Ser., M:451–468.

Nisbet, E.G., 1989. The end of the ice age. *Can. J. Earth Sci.,* 27:148–157.

Oppo, D.W., and Lehman, S.J., 1993. Mid-depth circulation of the subpolar North Atlantic during the last glacial maximum. *Science,* 259:1148–1152.

Paull, C.K., Buelow, W.J., Ussler, W., III, and Borowski, W.S., 1996. Increased continental margin slumping frequency during sea-level lowstands above gas hydrate-bearing sediments. *Geology,* 24:143–146.

Paull, C.K., Matsumoto, R., Wallace, P.J., et al., 1996. *Proc. ODP, Init. Repts.,* 164: College Station, TX (Ocean Drilling Program).

Paull, C.K., Ussler, W., III, and Dillon, W.P., 1991. Is the extent of glaciation limited by marine gas-hydrates? *Geophys. Res. Lett.,* 18:432–434.

Pickart, R.S., and Smethie, W.M., Jr., 1993. How does the deep western boundary undercurrent cross the Gulf Stream? *J. Phys. Oceanogr.,* 23:2602–2616.

Popenoe, P., Schmuck, E.A., and Dillon, W.P., 1993. The Cape Fear landslide: slope failure associated with salt diapirism and gas hydrate decomposition. *In* Schwab, W.C., Lee, H.J. and Twichell, D.C., (Eds.), *Submarine Landslides: Selective Studies in the U.S. Exclusive Economic Zone.* U.S. Geol. Surv. Bull., 2002:40–53.

Ruddiman, W.F., Kidd, R.B., Thomas, E., et al., 1987. *Init. Repts. DSDP,* 94 (Pts. 1 and 2): Washington (U.S. Govt. Printing Office).

Schmitz, W.J., Jr., and McCartney, M.S., 1993. On the North Atlantic circulation. *Rev. Geophys.,* 31:29–49.

Sheridan, R.E., Gradstein, F.M., et al., 1983. *Init. Repts. DSDP,* 76: Washington (U.S. Govt. Printing Office).

Shipley, T.H., Houston, M.H., Buffler, R.T., Shaub, F.J., McMillen, K.J., Ladd, J.W., and Worzel, J.L., 1979. Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises. *AAPG Bull.,* 63:2204–2213.

Silva, A.J., Hollister, C.D., Laine, E.P., and Beverly, B.E., 1976. Geotechnical properties of deep sea sediments: Bermuda Rise. *Mar. Geotechnol.,* 1:195–232.

Stommel, H., 1958. The abyssal circulation. *Deep-Sea Res.,* 5:80–82.

Tucholke, B.E., Bryan, G.M., and Ewing, J.I., 1977. Gas-hydrate horizons detected in seismic-profiler data from the western North Atlantic. *AAPG Bull.,* 61:698–707.

Ussler, W., III, and Paull, C.K., 1995. Effects of ion exclusion and isotopic fractionation on pore water geochemistry during gas hydrate formation and decomposition. *Geo-Mar. Lett.,* 15:37–44.

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